Performance Evaluation of a Magneto Plasma Sail

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A Magneto Plasma Sail (MPS) obtains thrust using the interaction between the solar wind and a magnetic field expanded by injected plasma. Although there have been many studies on this new propulsion system, ultimate performance available for the MPS is still unclear. Using ideal MHD models, we calculate the performance such as thrust or thrust to power ratio in order to clarify the engineering feasibility of the MPS. After a series of calculations, we found that for a spacecraft with a radius of 300m and a magnetic field of 0.02T, the MPS can achieve a thrust to power ratio of 0.6N/kW and a specific impulse of 3500s, which are much larger than those of ion thrusters.

1. Introduction

A magnetic sail obtains thrust using the interaction between the solar wind and the artificial magnetic field produced around a spacecraft (Fig. 1) [I. Funaki, 2003] [R.M. Winglee, 2000]. However, in order to capture the solar wind with low density, the magnetic sail requires a huge superconducting coil with a diameter of approximately 100km which is not feasible from the engineering point of view(Fig. 2) [R. Zubrin, 1991].

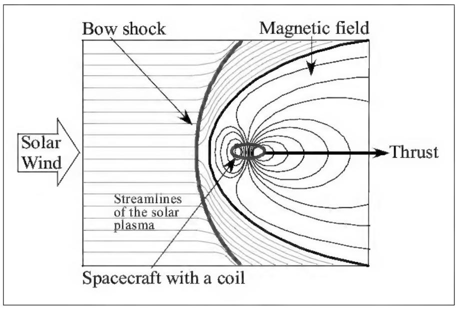

Fig. 1. Thrust Production of a Magnetic Sail

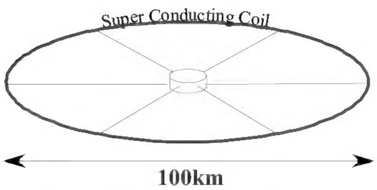

Fig. 2. Structure of a magnetic sail.

Consequently, another method to produce a huge magnetosphere must be considered. One of such methods is to expand a small magnetic field by a coil or a permanent magnet using the plasma injection from the spacecraft. When a supersonic plasma is injected from inside the magnetic field, the magnetic filed is frozen into the plasma flow and thus is expanded far away from the center [R.M. Winglee, 2000]. This method is known as a mini-magnetospheric plasma propulsion (M2P2), which was originally proposed by Winglee's group of the University of Washington, or a magneto plasma sail (MPS) called in this study (Fig. 3). Since the MPS can obtain thrust without consuming a large amount of the propellant or the electric power, it is expected to achieve large thrust to power ratio and high specific impulse (Isp).

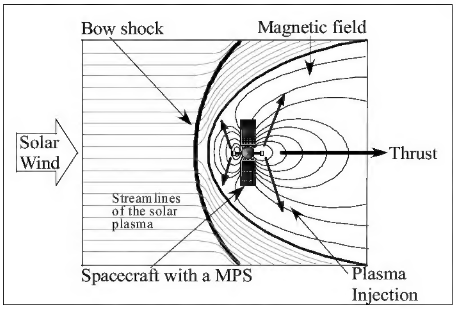

Fig. 3. Thrust Production of a MPS

Although many theoretical studies on MPS have been done so far, the ultimate performance of the MPS is not clear yet. Consequently, the purpose of this study is to calculate the performance using the following equation [I. Funaki, 2003].

$$F = C_D \frac{1}{2} \rho_{sw} u_{sw}^2 S \qquad (1)$$

where F, C_D, ρ_{sw}, u_{sw}, S is the thrust, the drag coefficient, the density and velocity of the solar wind, and the cross section of the magnetosphere. The contents of this paper can be summarized as follows:

1) Simulation based on two-dimensional ideal MHD model of the interaction between the solar wind and the magnetic field. Derivation of the drag coefficient C_D.
2) Simulation based on two-dimensional ideal MHD model of the magnetic field inflation by the plasma injection. Formulation of the magnetic field inflation by introducing two parameters, the inflation parameter and the frozen-in point.
3) Calculation of the thrust to power ratio, and the specific impulse (Isp) using equation (1). Optimization of the performance and size of the MPS.

2. MHD analysis of the MPS

2.1 The interaction between the solar wind and the magnetic field

The numerical results of the interaction between the solar wind and the magnetic field are obtained as follows.

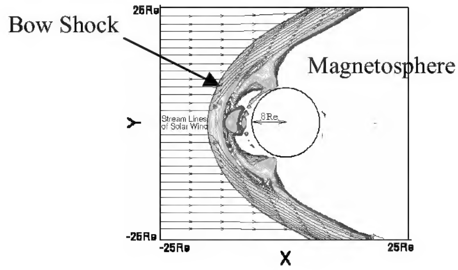

Fig. 4a. Solar wind density

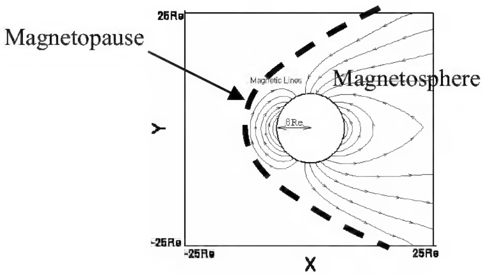

Fig. 4b. Magnetic field lines

The upper figure shows the solar wind density distribution and the lower one shows the magnetic field lines. According to these figures, the bow shock, magnetosphere, and magnetopause are confirmed. the drag coefficient calculated using the numerical results is C_D=1.6.

2.2 The magnetic field inflation

An example of simulation results of the magnetic field inflation by the plasma injection is obtained as follows.

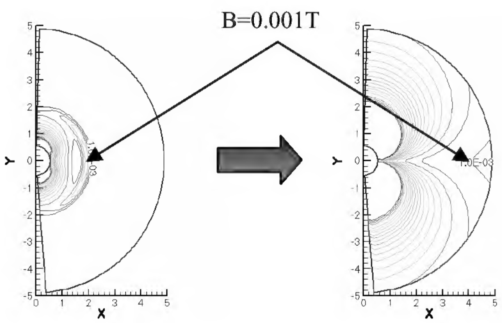

Fig. 5a. Magnetic field density at t=0.1ms

Fig. 5b. Magnetic field density at t=1ms

It is obvious that the magnetic field is expanded by the plasma injection as the time alters from 0.1ms to 1ms. The characteristics of the magnetic field inflation are modeled using these numerical results for various plasma injection, and then the size of the magnetosphere is calculated.

3. Performance evaluation of the MPS

The thrust to power ratio, Specific impulse (Isp), minimum size of the MPS corresponding various β_0 plasma injection are as follows. β_0 represents the ratio of the plasma dynamic pressure to the magnetic pressure.

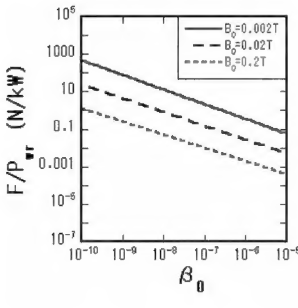

Fig. 6a. Thrust to power ratio with various β_0

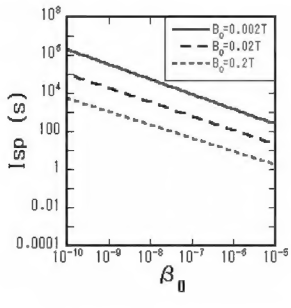

Fig. 6b. Specific Impulse with various β_0

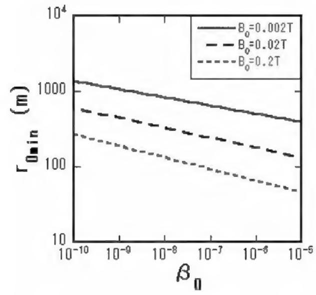

Fig. 7. Minimum size of the MPS.

After a series of calculation, we found that for a spacecraft with a radius of 300m and a magnetic field of 0.02T, the MPS can achieve a thrust of 25N and a thrust to power ratio of 540mN/kW, which are much larger than those of ion thrusters.

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